Observations on the tilting of multi-story buildings founded on Pliocene sands in Maputo, Mozambique

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Abstract: The capital city of Mozambique, Maputo is built mainly on the Pliocene Formacao da Ponte Vermelha which comprises, in the upper part, poorly cemented ferruginous red sandstones and silty sand passing gradually down into yellow sand. It is a modern city with many high-rise domestic and commercial buildings. The south east of the city is situated on high ground at the mouth of the Maputo River with a steep slope leading down to a coastal plain to the east. In this area, some of the buildings at the top of the slope, along the Avenida Fredrich Engels were observed to have acquired a tilt that first became noticeable in the 1990s.

This paper describes the geological and geomorphological setting, examines a number of possible mechanisms that might be the cause of the tilting and suggests which is the most likely cause for further investigation.

Résumé: Maputo, la capitale du Mozambique, est construite principalement sur le « Pliocene Formacao da Ponte Vermelha » qui est constitué, dans sa partie supérieure, de grès rouge ferrugineux mal cimenté et de sable silteux passant progressivement dans le sable jaune. Il s'agit d'une ville moderne ayant un grand nombre de tours résidentielles et commerciales. Le sud-est de la ville est situé en hauteur à l'embouchure du fleuve Maputo avec une forte pente en direction de la plaine côtière à l'est. Dans cette zone, il a été observé que quelques bâtiments se trouvant en haut de la pente, le long de l'Avenida Fredrich Engels, ont acquis une certaine inclinaison tout d'abord remarquée dans les années 1990. Cet article décrit le contexte géologique et géomorphologique, examine un certain nombre de mécanismes possibles pouvant être la cause de l'inclinaison et suggère quelle est la cause la plus probable méritant d'être examinée de manière plus approfondie.

Keywords: cohesionless materials, engineering geology, foundations, sand,

INTRODUCTION

The capital city of Mozambique, Maputo is built mainly on the Pliocene Formacao da Ponte Vermelha which comprises, in the upper part, poorly cemented ferruginous red sandstone and silty sand passing gradually down into yellow sand. It is a modern city with many high-rise domestic and commercial buildings. The south east of the city is situated on high ground at the mouth of the Maputo River at the top of a steep slope of approximately 40º leading down to a coastal plain to the east. In this area, some of the buildings at the top of the slope, between Avenida Julius Nyerere and Avenida Fredrich Engels (Fig 1.) were observed to have acquired a tilt that first became noticeable in the 1990s. The reason for the tilt was not readily apparent and a desk study and visit to six of the affected buildings were carried out to investigate the phenomena (Forster 2001).

GEOLOGICAL BACKGROUND

The area under investigation is on the coastal slope that forms the eastern boundary of the City of Maputo (Fig.1). It falls on the 1:50 000 geological sheet 2532 D3 Maputo (Ferrara *et al.* 1995).

Table 1. Stratigraphy of the geological deposits around Maputo.

Quaternary	Holocene	Beach and tidal deposits	Qm	White sand and mud, in part temporarily submerged.
		Alluvial deposits	Qa	Fluvial dark clays with carbonaceous intercalations of marine influence (estuarine clays).
		Xefina Formation	QXf	Coastal dune sand, with ilmenite sand
Tertiary	Pliocene	Ponta Vermelha Formation	TPv	Silty and red sands passing into yellow sandstone, locally with a ferruginous crust.
	Pliocene / Miocene	Santiago Formation	TSa	Clay and calcareous sandstone with *Ostrea cullata* in the upper part.
	Oligocene	Inharrime Formation	Tin	Fine sandstone, silty and clayey, impregnated with organic material intercalated with calcareous sandstones.

The coastal slope on the eastern side of the city comprises material of the Ponta Vermelha Formation (TPv). At the foot of the slope there is an outcrop of the Xefina Formation (QXf) that extends eastwards to the coast where materials of the Beach and tidal deposits (Qm) extend below the high water line.

A fault trending NNE/SSW runs parallel to the coast and marks the boundary between the Ponta Vermelha Formation to the west and the Xefina Formation to the east. The down throw is to the east of about 25 m.

To the south of the City the coastal slope curves inland along the estuary of the River Maputo leaving a 100 m wide strip of Alluvial deposits (Qa) between its foot and the coast.

The geological sheet notes (Momade *et al*. 1996) describe the Ponta Vermelha Formation as follows:-

In the upper part ferruginous sandstones and silty red sand passing gradually down into yellow and white sand respectively. Locally there is a red ferruginous crust possibly of lateritic origins. This passes downwards into white calcareous sand - horizontally stratified. The TPv passes into the Santiago Formation at borehole SM2 to the north east of the city at a depth of about 35m (approximately sea level).

An exposure in a sand quarry at Albazinie north of Maputo shows the Ponta Vermelha Formation to be remarkably uniform in its composition with no visible variation in lithology or structure (Fig. 2). The quarry walls stand at a steep angle, almost vertical in places where material is being worked. The sand could be easily crushed by hand.

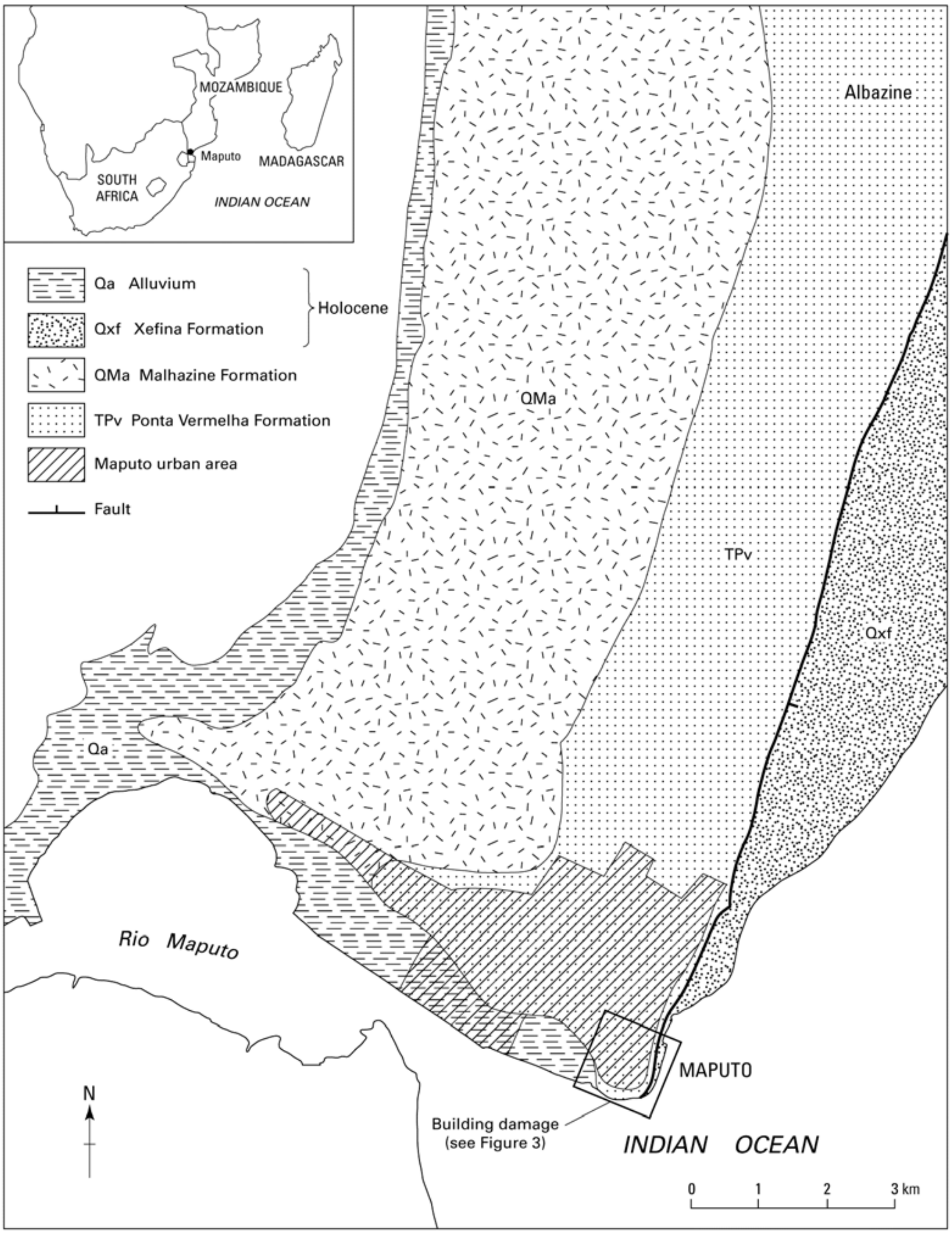

Figure 1. Geology of the Maputo area and location of the site of the damaged buildings.

GEOTECHNICAL PROPERTIES

A site investigation report was available for a site adjacent to the Cinema Xenon (Fig. 3) close to where the tilted buildings were situated. Two cable percussion holes had been drilled to 20 m. They proved 4.5 m and 1.5 m of made ground on the Ponta Vermelha Formation – fine to medium red sand to 10.5 m, fine red sand to 20 m. Visual inspection of the surface exposed at the site showed it to be very uniform in composition.

Figure 2. Sand quarry in Ponta Vermelha Formation at Albazinie.

The results of tests on seven samples indicated that it was predominantly a well-sorted fine to medium sand that comprised, 20% clay + silt, 75% fine / medium sand and 5% coarse sand. The material was non-plastic or of very low plasticity and Standard Penetration Tests indicated that it was generally loose to medium dense becoming dense with increasing depth (Table 2).

Table 2. Summary geotechnical properties from boreholes 1 and 2 adjacent to the Xenon Cinema, Maputo

		SPT			Plasticity				
Sample	Depth	Seating Blows	Drive blows	LL	PL	PI	Cu	phi	Permeability
	metres	150mm	300mm	%	%	%	kg/cm^2	degrees	cm/sec
BH1			N'						
563	1	1	8						
553	3	2	6						
554	4.5	2	7						
551	6.5			17	13	4	0.3	34	1.15×10^{-8} to 5.17×10^{-9}
555	7.5	3	8	18	12	6			
556	9	4	15						
557	10.5	4	18						
558	13.5	4	12						
559	15	5	25	17	13	4			
560	16.5	5	23						
561	18	10	41						
562	19.5	12	47						
BH2									
616	6	3	7	16	12	4			
618	7.5	5	20						
624	9.5			NP			0.2	40	1.23×10^{-8} to 4.37×10^{-9}
619	10.5	5	24						
620	13.5	7	27						
621	15	10	33	NP					
622	16.5	4	9						
617	18.5	7	39						
623	19.5	16	50						

BUILDING DAMAGE

The buildings that showed an obvious tilt were located between the eastern side of Avenida Julius Nyerere and Avenida Frederich Engels at the top of the steep coastal slope (Fig. 3).

Site 1 Avenida Julius Nyerere

This was the most severely tilted building (Fig. 4). It comprised 10 floors (incuding the ground floor) and was approximately 30 m high and 15 m wide. It was built in 1960 but the tilting started many years later (1990s). The present backward tilt has been measured at its highest point of contact with the adjacent building as 0.37 m and the side tilt 0.15 m to the right (as seen facing the building) (Fig. 4). The damage seen at ground level at the back of the building was due to the backward and sideways rotation of the building causing it to crush the end of the right hand side boundary wall and damage a single story construction on the left hand side (Fig. 5). The caretaker reported that after the start of the movement the mains water supply pipe to the building was found to be damaged and the surrounding soil was in a saturated condition. It was not known if the fractured pipe preceded the movement or was a result of the movement. The pipe had been replaced and a new water tank installed on the ground surface to replace the one that had been damaged.

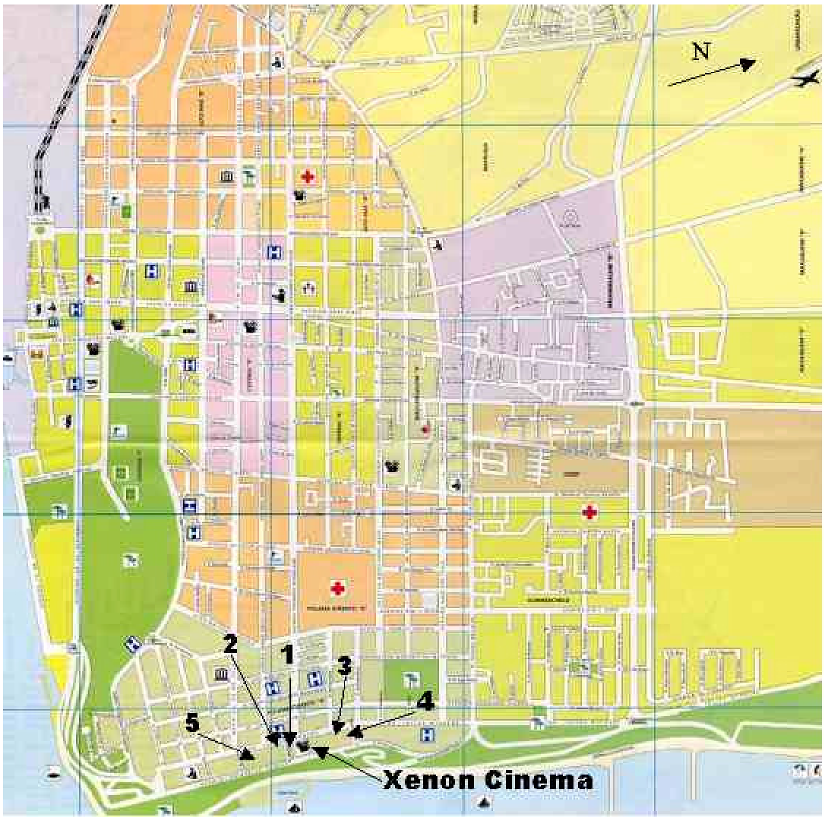

Figure 3. Location of buildings where tilting was observed

Figure 4. Site 1, Avenida Julius Nyerere

Site 2 Avenida Julius Nyerere

The second building comprised eight stories and was approximately 25 m high and 13 m wide. The backward tilt and leftward tilt were about 0.25 m and 0.15 m respectively relative to the uppermost point of contact with the adjacent building when viewed from across the road. The side tilt was towards a free space where Momoni Street passed through the building line. It was also apparent that the building had dropped vertically at the front, relative to it neighbour, by about 0.02 m.

Figure 5. Site 1, damage to a single story construction on the left hand side at the back of the building.

Site 3 Avenida Julius Nyerere

This building comprised eight floors and was about 25 m high by about 12 m wide. The building appeared to have tilted back relative to it neighbour by about 0.1 to 0.15 m at its top.

Site 4 Avenida Julius Nyerere

The building was on the corner of Avenida Julius Nyerere and Nkunya-Kilido Street opposite the Banco Formento. The building was 15 stories high and had a lower extension at the back of about seven stories. The side of the building was clad in small mosaic tiles that showed a fracture pattern as a series of en echelon cracks at the junction of the main building and rear extension. The damage was different to the other buildings inspected on Avenida Julius Nyerere and was consistent with differential settlement across the foundation of the building due to the greater loading imposed by the higher part of the building which had caused greater settlement than the low-rise extension and had thus caused a series of shear failures to occur at each floor level where the two parts of the building joined. Cracking was also visible at the base of the front of the building. The damage to this building, which was known to the local engineers to include internal structural damage as well as the external cracking, was different to that shown by the tilted buildings and it is probable that it was due to a different process.

Site 5 Avenida Julius Nyerere

The fifth building comprised eight stories and was about 40 m high and 15 wide. The site was on the east side of the street. It appeared to have tilted back by about 0.35 m and to the left by about 0.10m relative to its neighbours. It had also moved vertically down at the front relative to adjacent buildings by about 0.02 to 0.03 m.

BUILDING DAMAGE AND GEOLOGICAL PROCESSES

If the damage at site 4 can be attributed to a different process than that causing tilting and it may be excluded from consideration of the interaction of geological processes and foundations that could have caused of the tilting of the other buildings.

Possible geological processes that might cause the observed damage are:

- Deep-seated rotational failure.

- Differential settlement over a lens of weaker material under the back of the buildings as a result of long term consolidation
- Removal of material from below the foundation at the back of the buildings by internal erosion (water flow)

Deep-seated failure is rejected as a cause on the grounds that the direction of movement is towards the slope whereas a rotational failure would cause it to be away from the slope. Also, no evidence of deep rotational failures was seen on the slope or on the ground surface near to the buildings.

Differential settlement over a lens of weaker material would appear unlikely from the evidence of the borehole test results on the site next to the Xenon Cinema. These indicate a very uniform lithology of increasing density with depth to at least 20m below the ground surface.

The removal of material by internal erosion due to a flow of water would be a strong possibility for a building founded on silty sand since the silt component may be removed by flow through the intergranular pore spaces. It is likely that this process was responsible for the worsening of the tilt on site 1 following the fracturing of the water supply pipe to the building but if an earlier leakage from the pipe was the cause of the initial tilt is not known. The original water supply tank below the ground surface at the back of the building was believed to be of concrete construction and it is possible that it may have cracked due to settlement and have leaked for a considerable time causing a slow subsidence that eventually fractured the supply pipe that fed water into it. If such a leakage were to be the cause it would have to be accepted that all four buildings had suffered from a similar leaking water tank at the back of the building and this would be an unlikely coincidence.

It was noted that the ground in front of the building line was covered by relatively impermeable surfaces of the road and pavement that would not allow significant infiltration by surface water to the ground below. Some direct infiltration into the ground behind the buildings may have occurred through the gardens of the low-rise buildings on Avenida Fredrich Engels but, generally, the surface at the back of the buildings was also covered by concrete and it was believed that surface rainwater from the roof and yard behind each site was directed away from the site to a public drain and not disposed of to a soak-away at the rear of the building. However, some doubts have been expressed by local engineers as to the capacity and integrity of the drainage system to cope with the flow of surface (and other water) particularly during storms such as the extreme rainfall that lead to the flooding of 2000 may have put a severe strain on the drainage network (Forster 2004).

The fact that four buildings situated close to each other have suffered very similar damage implies a causal factor that is common to all four. Since they are all similar in age, dimensions and design, it would be worth considering a common flaw in their design or construction. However, to explore this line of investigation would require their design plans to be located and compared. It would also be beneficial to compare their design with those of adjacent buildings of similar and greater height to see if there is a factor that explains why these buildings have failed and others have not. It is possible that taller buildings are founded at a greater depth and thus avoid the problem.

The fact that they are all on the same side of Avenida Julius Nyerere as the coastal slope behind Avenida Fredrich Engels suggests that it is more than coincidence and it may be that the proximity of the slope is involved in the cause of movement in some way. The buildings are all located on the road where it is at its closest to the coastal slope.

If there is some degree of infiltration from the surface and leakage from services it is feasible that groundwater will migrate laterally towards the free face of the coastal slope. It is likely that the flow will be greatest in the upper few metres where the sand is in a loose condition rather than downwards where the sand is in a medium dense or dense condition. If this assumption were correct then internal erosion would be concentrated in the upper zone (0 to 10 m?). The surface result of this might be expected to be a gentle lowering of the surface too small and slow to be detected but the effect on friction piles founded in this zone may be to decrease their bearing capacity, those closest to the slope being the worst effected. Taller buildings would have longer piles founded at greater depth and, for a greater proportion of their length, below the affected zone. Therefore, they might not be affected by a slight loss of bearing capacity in their upper part and it is possible that at their base, in very dense sand, a greater end-bearing element might be mobilised to compensate for any small losses of friction.

CONCLUSIONS

Damage to five buildings was examined in Maputo. The damage to one of these was attributed to flaws in foundation design. The cause of the damage to the remaining four was not readily apparent. It was unlikely that landslides on the coastal slope were a contributory cause. Uniform lithology with a normal strength profile increasing with depth was confirmed to a depth of twenty metres on a site adjacent to the Xenon Cinema close to the damaged buildings. Internal erosion of fines from the back of the buildings was a process that appeared to offer the most likely mechanism consistent with the observed features.

It should be recognised that the movement of the tilted buildings has been seen and measured only by their relative displacement from their neighbours. It is possible that their neighbours may also be tilted and that buildings standing in isolation have tilted but are unrecognised because there is no reference point from which to measure.

Regarding future actions to deal with the problem continued monitoring of the amount and rate of increase of the tilt would be advisable and remedial actions would probably be best directed at stabilising the movement by drainage or underpinning. Restoring the buildings to the vertical is unlikely to be cost effective in view of the likely cost of such works and the relatively minor inconvenience of the tilting which is currently insufficient to significantly impair the function of the buildings.

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